Cosmic antiprotons as a probe for neutralino dark matter?

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Abstract

The flux of cosmic ray antiprotons from neutralino annihilations in the galactic halo is computed for a large sample of models in the Minimal Supersymmetric extension of the Standard Model. We also revisit the problem of estimating the background of low-energy cosmic ray induced secondary antiprotons, taking into account their subsequent interactions (and energy loss) and the presence of nuclei in the interstellar matter.

We point out that in some cases the optimal kinetic energy to search for a signal from supersymmetric dark matter is above several GeV, rather than the traditional sub-GeV region. The large astrophysical uncertainties involved do not allow the exclusion of any of the MSSM models we consider, on the basis of current data.

1 Introduction

Among the most plausible candidates for the dark matter in the Universe are Weakly Interacting Massive Particles (WIMPs), of which the supersymmetric neutralino is a favourite candidate (see e.g. Jungman et al., 1997 for a review). We will here consider the antiproton flux from neutralino dark matter annihilating in the galactic halo and we will also investigate the prospects of seeing such a signal above the conventional background.

As antimatter seems not to exist in large quantities in the observable Universe, including our own Galaxy, any contribution to the cosmic ray generated antimatter flux (besides antiprotons also positrons) from exotic sources may in principle be a good signature for such sources. This issue has recently come into new focus thanks to upcoming space experiments like PAMELA (Adriani et al., 1995) and AMS (Ahlen et al., 1994) with increased sensitivity to the cosmic antimatter flux.

2 Definition of the supersymmetric model

We work in the minimal supersymmetric standard model with seven phenomenological parameters and have generated about 10^5 models by scanning this parameter space (for details, see Bergström et al., 1999). For each generated model, we check if it is excluded by recent accelerator constraints of which the most important ones are the LEP bounds (Carr, 1998) on the lightest chargino mass (about 85–91 GeV), and the lightest Higgs boson mass $m_{H_2^0}$ (which range from 72.2–88.0 GeV) and the constraints from $b \rightarrow s\gamma$ (Ammar et al., 1993 and Alam et al.,1995).

For each model allowed by current accelerator constraints we calculate the relic density of neutralinos $\Omega_\chi h^2$ where the relic density calculation is done as described in Edsjö and Gondolo (1997), i.e. including so called coannihilations. We will only be interested in models where neutralinos can be a major part of the dark matter in the Universe, so we restrict ourselves to relic densities in the range $0.025 < \Omega_\chi h^2 < 1$.

3 Antiproton production by neutralino annihilation

Neutralinos are Majorana fermions and will annihilate with each other in the halo producing leptons, quarks, gluons, gauge bosons and Higgs bosons. The quarks, gauge bosons and Higgs bosons will decay and/or form jets that will give rise to antiprotons (and antineutrons which decay shortly to antiprotons). The hadronization for all final states (including gluons) is simulated with the well-known particle physics Lund Monte Carlo program PYTHIA 6.115 (Sjöstrand, 1994).

To calculate the source function of $\bar{p}$ from neutralino annihilation we also need to specify the halo profile. We we will here focus on the modified isothermal distribution with a local halo density of 0.3 GeV/cm^3.

4 Propagation model and solar modulation

We choose to describe the propagation of cosmic rays in the Galaxy by a transport equation of the diffusion type as written by Ginzburg and Syrovatskii (1964) (see also Berezinskii et al., 1990; Gaisser, 1990).

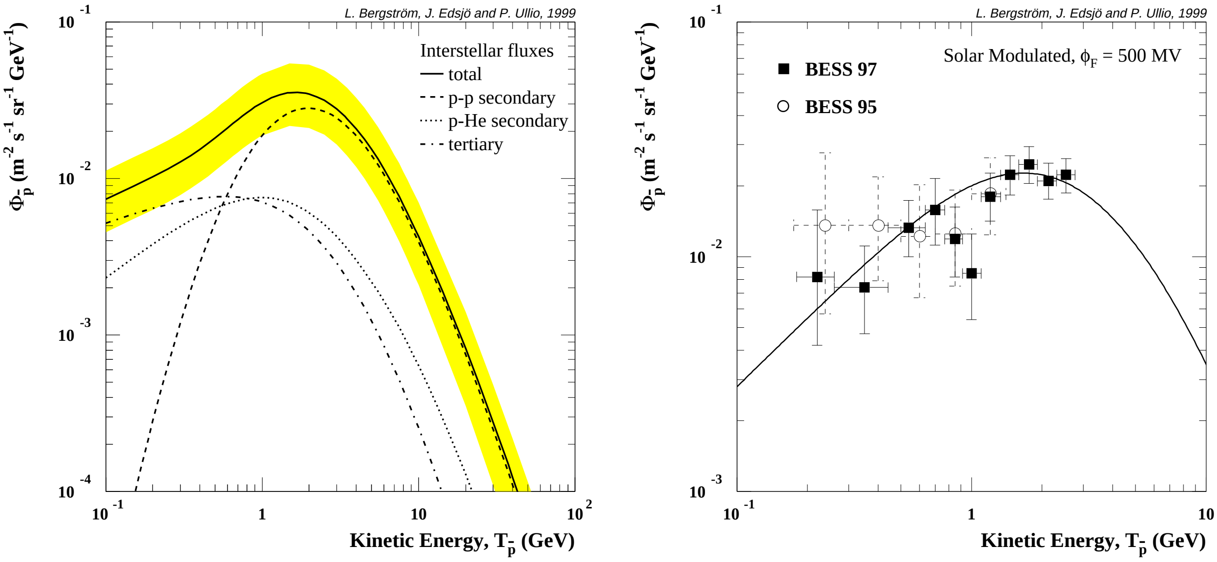

Figure 1: a) The interstellar antiproton flux and the contribution from secondary and tertiary (i.e. $\bar{p}$s that have lost energy) antiprotons. The uncertainty due to the parametrization of the primary proton spectrum is also given as the shaded band. b) The same as the solid line in a) but solar modulated with $\phi_F = 500$ MV. The BESS 95 and 97 data are also shown (Matsunaga et al., 1998; Orito, 1998).

The propagation region is assumed to have a cylindrical symmetry: the Galaxy is split into two parts, a disk of radius R_h and height $2 \cdot h_g$, where most of the interstellar gas is confined, and a halo of height $2 \cdot h_h$ and the same radius. We assume that the diffusion coefficient is isotropic with possibly two different values in the disk and in the halo, reflecting the fact that in the disk there may be a larger random component of the magnetic fields. For the diffusion coefficient, we assume the same kind of rigidity dependence as in Chardonnet et al. (1996) and Bottino et al. (1998), i.e. that $D(R) = D^0 \left(1 + R/R_0\right)^{0.6}$. As a boundary condition we assume that the cosmic rays can escape freely at the border of the propagation region. For details about our propagation model and how the solutions are obtained, see Bergström et al. (1999).

For the solar modulation we use the analytical force-field approximation by Gleeson & Axford (1967; 1968) for a spherically symmetric model. To compare with the two sets of BESS measurements, which are both near solar minimum, we choose the modulation parameter $\phi_F = 500$ MV.

5 Background estimates

Secondary antiprotons are produced in cosmic ray collisions with the interstellar gas. Normally, only $p-p$ interactions are included, which gives rise to a 'window' at low energies with low fluxes. However, we include $p-He$ interactions as well as $p-p$ interactions and also energy losses during propagation (with the full energy distribution). Both of these processes tend to enhance the antiproton flux at low energies and in Fig. 1 (a) we show the background flux of antiprotons and the contributions from $p - He$ interactions and energy losses. We clearly see that the low-energy window has been filled-in. In Fig. 1 (b) we show the solar modulated curve compared with recent BESS measurements. We see that data is well described by this conventional source alone.

6 Signal from neutralino annihilation

In Fig. 2 (a) we show the solar modulated fluxes versus the neutralino mass. We see that there are many models with fluxes above the BESS measurements. However, this conclusion depends strongly on which range one allows for the neutralino relic density. In Fig. 2 (a) we have coded the symbols according to the relic density interval. As can be seen, essentially all models which are in the BESS measurement band have a relic density $\Omega_\chi h^2 < 0.1$. If we instead require $0.1 \lesssim \Omega_\chi h^2 \lesssim 0.2$ the rates are never higher than the measured

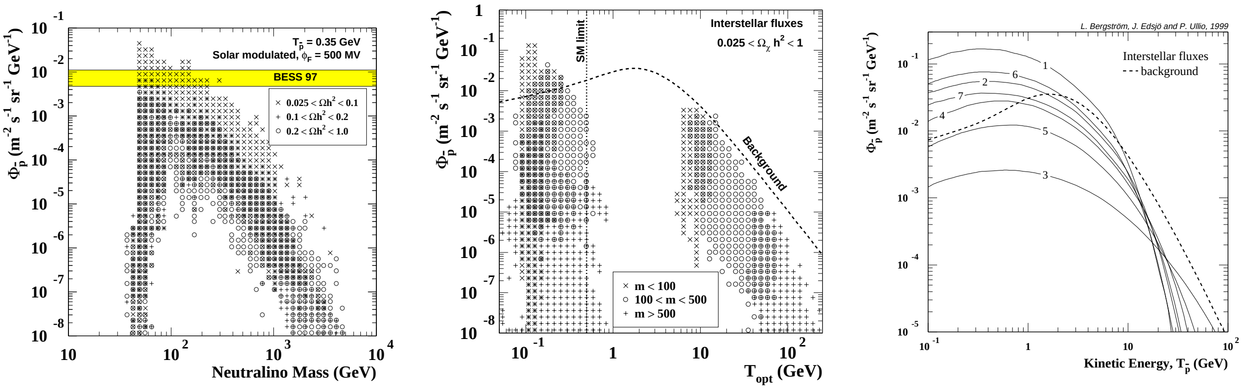

Figure 2: (a) The solar modulated antiproton fluxes at 0.35 GeV compared with BESS 97. The models have been coded according to their relic density, $\Omega_\chi h^2$. In (c) we show the flux of antiprotons from neutralino annihilation at the optimal kinetic energy, $T_{\rm opt}$, versus $T_{\rm opt}$. $T_{\rm opt}$ is defined as the energy at which $\Phi_{\rm signal}/\Phi_{\rm background}$ is highest and if the spectrum has more than one optimum, the highest two have been included in the plot. The models have been coded according to the neutralino mass in GeV. In (c) we show the antiproton spectra for 7 example models.

flux.

This points to a weakness of this indirect method of detecting supersymmetric dark matter: once the predicted rate is lower than the presently measured flux, the sensitivity to an exotic component is lost. This is because of the lack of a distinct signature which could differentiate between the signal and the background.

We are now interested in finding out if there are any special features of the antiproton spectra from neutralino annihilation which distinguish these spectra from the background. We then ask ourselves if there is an optimal energy at which $\Phi_{\rm signal}/\Phi_{\rm background}$ has a maximum. In Fig. 2 (b) we show the interstellar flux at these optimal energies, $T_{\rm opt}$, versus $T_{\rm opt}$. We have two classes of models: one class which have highest signal to noise below 0.5 GeV (i.e. inaccessible in the solar system due to the solar modulation) and one which have highest signal to noise at 10–30 GeV. For this first class of models, we note that there exists a proposal of an extra-solar space probe (Wells et al., 1998) which would avoid the solar modulation problem and is thus an attractive possibility for this field. However, these models have high rates in the range 0.5–1 GeV as well, even though it would be even more advantageous to go to lower energies. The second class of models are much less affected by solar modulation and also give reasonably high fluxes.

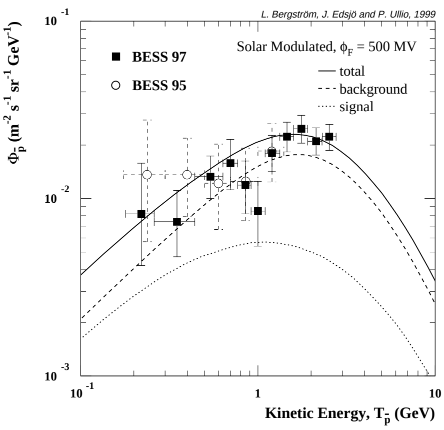

Figure 3: An example of a composite spectrum consisting of our reference background $\bar{p}$ flux (Fig. 1 (b)) reduced by 24 % with the addition of the predicted flux from annihilating dark matter neutralinos of MSSM model number 5.

In Fig. 2 (c) we show some examples of spectra. They show maxima occurring at lower energies than for our canonical background. At higher energies, the trend is that the slope of the flux decreases as the neutralino mass increases. Model number 3 corresponds to a heavy neutralino and its spectrum is significantly less steep than the background. If such a spectrum is enhanced, for instance by changing the dark matter density distribution, we would get a bump in the spectrum above 10 GeV (Ullio, 1999).

Finally, in Fig. 3 we show an example of a hypothetical composite spectrum which consists of our canonical background flux decreased by 24 % (obtained e.g. by decreasing the primary proton flux by 1σ), and the signal for model 5 in Fig 2 (c). We can obtain a nice fit to the BESS data, but as noted before, there are no special features in the spectrum that allow us to distinguish between this case and the case of no signal.

7 Discussion and conclusions

We have seen that there is room, but no need, for a signal in the measured antiproton fluxes. We have also seen that the optimal energy to look for when searching for antiprotons is either below the solar modulation cut-off or at higher energies than currently measured. However, there are no special spectral features in the signal spectra compared to the background, unless the signal is enhanced and one looks at higher energies (above 10 GeV).

We have stressed the somewhat disappointing fact that since the present measurements by the BESS collaboration already exclude a much higher $\bar{p}$ flux at low energies than what is predicted through standard cosmic-ray production processes, an exotic signal could be drowned in this background. Even if it is not, the similar shape of signal and background spectra will make it extremely hard to claim an exotic detection even with a precision measurement, given the large uncertainties in the predicted background flux (at least a factor of a few, up to ten in a conservative approach).

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